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HAROLD PALMER

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by

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Lieutenant Commander

Royal Canadian Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
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ABSTRACT

Expensive equipment procurement programmes have been required by the armed services to keep their communications receiving equipment compatible with current operating standards. This paper applies the results published in recent literature on the analysis and evaluation of the phase-locked loop demodulator to investigate the feasibility of improving the stability and selectivity characteristics of an aging communications receiver for satisfactory use in modern frequency-shift radio-teletype circuits.

The phase-locked loop used is analyzed and the loop circuits and modifications to the basic receiver are discussed. Frequency spectra photographs are included of the IF signal in the receiver for square-wave and sine-wave modulating signals.

The writer wishes to express his appreciation for the assistance given him by Professor P. E. Cooper and Professor O. H. Polk of the U. S. Naval Postgraduate School in this investigation.

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1.0 Introduction

The locked-loop has been used in various forms as an FM demodulator for many years. Two of the earlier applications of the basic principles were the Philco single-stage locked-in-oscillator and the RCA Beers receiver. Although the Philco receiver was used commercially to a considerable extent, neither it nor the Beers receiver provided outstanding advantages over the more conventional discriminators such as the Foster-Seeley and ratio circuits. It is primarily the studies undertaken in recent years in the radio telemetry field that have shown the phase-locked loop discriminator to be an efficient, if not near-optimum, frequency-modulation detector.

The primary object of this paper is to show the feasibility of applying the techniques and the methods of phase-locked loop analysis that have been developed and published in current literature to improving the operating characteristics of a conventional communications receiver. This will require the addition of phase-locked loop circuitry and some original circuit modification to enable the equipment to receive frequency-shift radio-teletype signals with stability and selectivity characteristics comparable to modern receivers.

Many expensive receiving equipment procurement programmes have been necessary recently because aging equipment provided only marginal service. The two most critical characteristics

that prevent older equipment complying with modern communications standards are their stability and selectivity.

The phase-locked loop has inherent characteristics that solve both the problems of selectivity and stability. It provides a frequency stability for the receiver that is equal to a simple, and generally inexpensive, fixed-frequency oscillator and a selectivity that is determined by the loop-filter characteristic rather than the IF selectivity of the receiver. Some of the phase-locked loop circuits developed operate after the second conversion. This investigation looks into loop circuitry that includes the first local oscillator and IF amplifier of the receiver which, in conventional receivers, are the prime stability and selectivity determining elements.

A secondary aim of the investigation is to determine if a conventional communications receiver could be made to operate with the advantages of phase-locked loop demodulation without requiring any major re-design of the basic receiver.

2.0 Scaling

Most interest in frequency-shift radio-teletype circuits is in the LF-MF-HF bands. The availability of equipment, primarily the Boonton Model 202B Signal Generator and Hallicrafters S-27 receiver, led the investigation into the VHF band. Selectivity curves and schematic diagrams for the S-27 receiver are included in Appendix I, II, and III.

With a scaling factor of ten, the results obtained at VHF can be compared to results expected in the HF band as shown in Table 1. Keying speeds are not affected by scaling.

TABLE 1

SCALED HF RESULTS FROM VHF EXPERIMENTAL TEST

	Experimental VHF Test	Scaled HF Results
RF Carrier	100 Mcs	10 Mcs
Frequency Shift	10 Kcs	1 Kcs
Keying Speed	100 cps (286 wpm)	100 cps (286 wpm)

3.0 Circuit Investigation and Modification

3.1 Local Oscillator

The two prime aims in carrying out the voltage-controlled oscillator modification to the local oscillator of the S-27 receiver were as follows:

a) No major re-design of the oscillator would be acceptable.

b) RF alignments of the modified circuit should continue to be possible with existing controls.

These two requirements excluded the more obvious method of constructing a voltage-controlled oscillator by adding a reactance-tube or voltage-capacitance semi-conductor device to the oscillator tank-circuit. The simplest remaining method of varying the frequency output of an established oscillator was to vary the plate supply voltage. Therefore, the plate voltage versus frequency characteristics of the local oscillator were investigated. Figure 1 shows that a reasonably linear relationship existed over approximately 65 kilocycles with a plate voltage variation in the order of 70 volts. It is noted that the oscillator, a reverse-feedback, plate-stabilized circuit, was originally designed to minimize the adverse stability effects of variations in the plate supply. Refer to Figure 2.

The plate load resistance is also a critical component in the stability of an oscillator. The curves of Figure 3

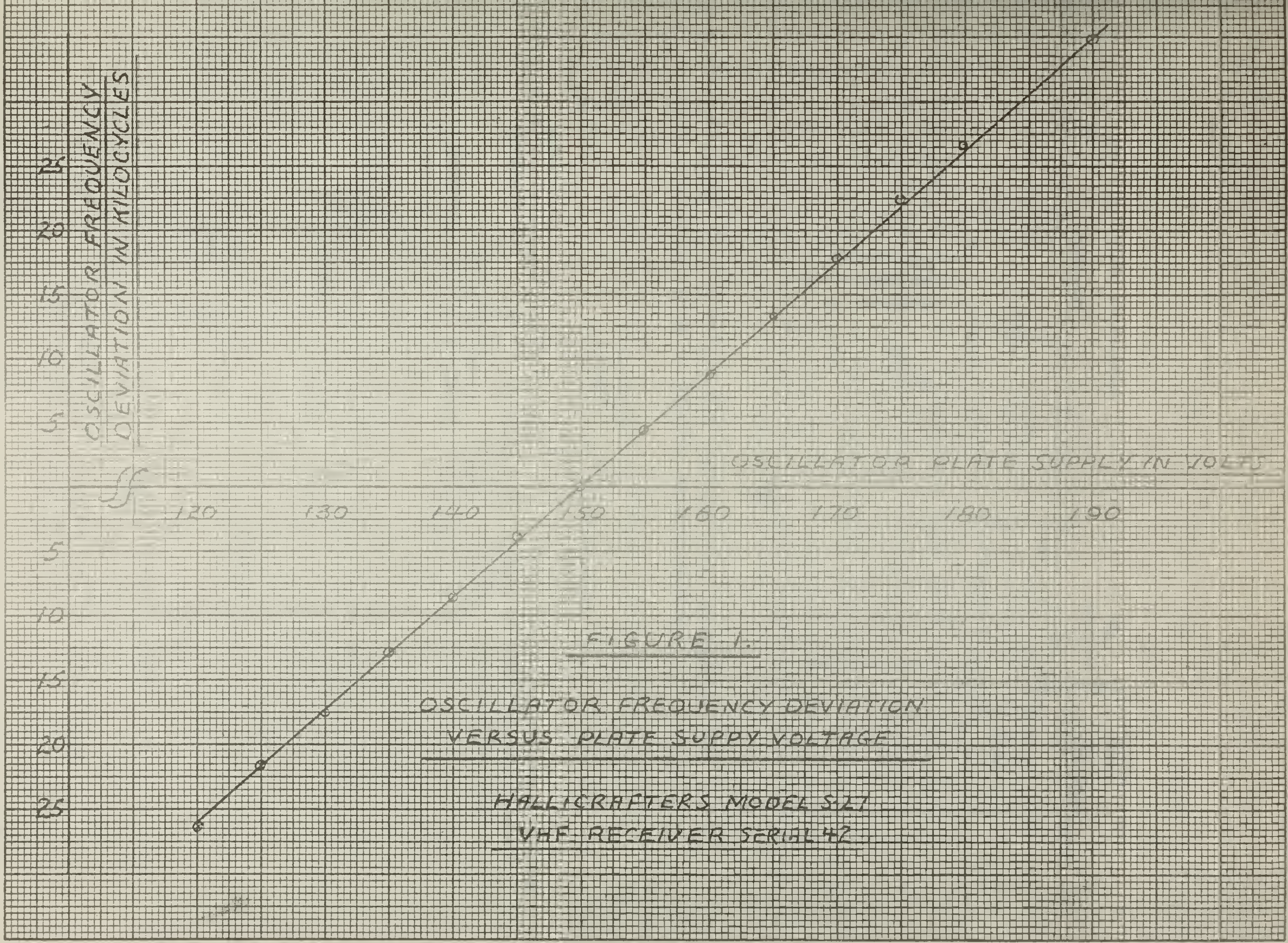


FIGURE 1.

OSCILLATOR FREQUENCY DEVIATION
VERSUS PLATE SUPPY VOLTAGE

HALLICRAFTERS MODEL S-27
VHF RECEIVER SERIAL 42

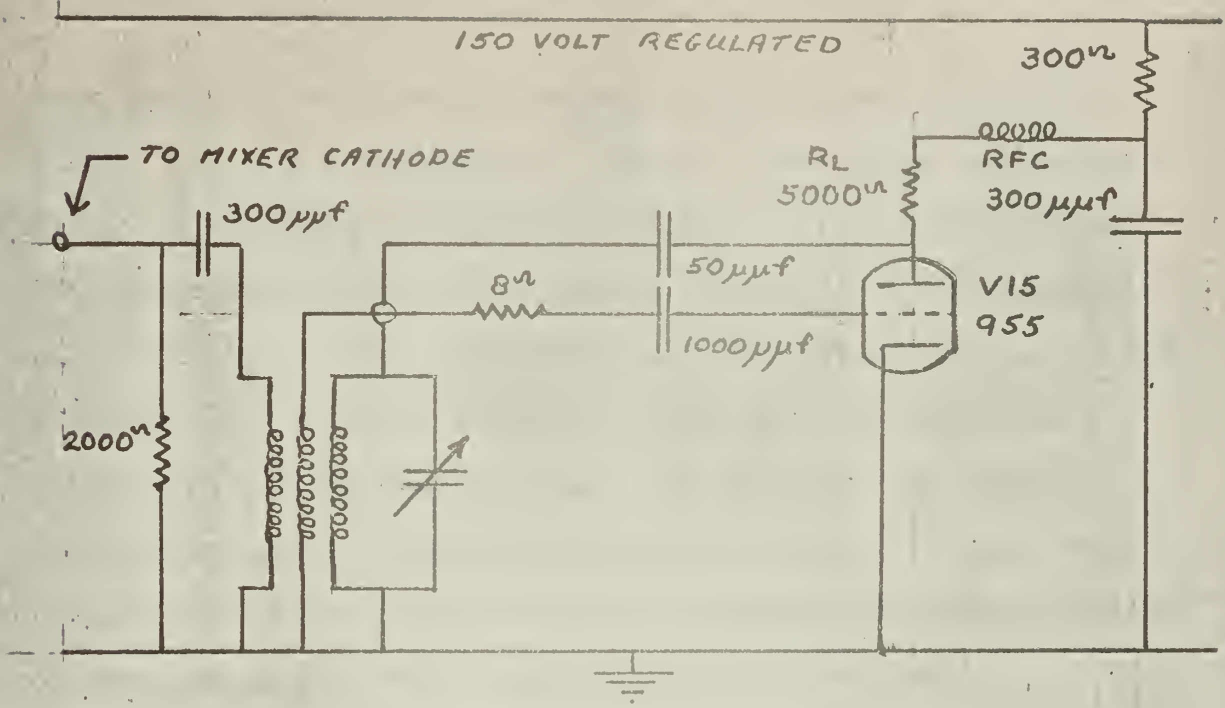


FIGURE 2. SIMPLIFIED SCHEMATIC DIAGRAM OF S-27 LOCAL OSCILLATOR

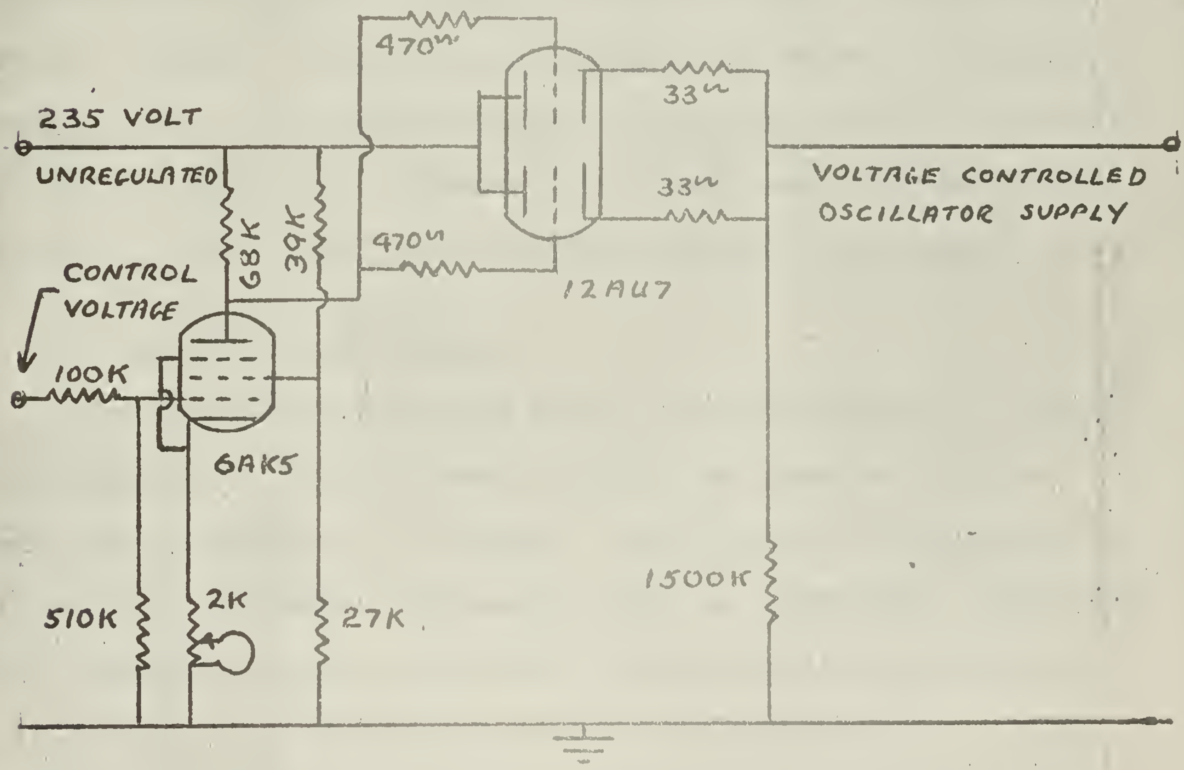


FIGURE 3. SCHEMATIC DIAGRAM OF VOLTAGE CONTROL CIRCUIT

were obtained to show the relationship of oscillator frequency and plate voltage for various plate load resistances. These curves show the control voltage of the conventional DC regulation circuit of Figure 4 rather than the actual plate voltage. The results of this investigation led to the lowering of the plate load from 5000 ohms to 4000 ohms to gain a greater frequency range. To provide the required plate voltage variation, the control circuit DC input was taken from the receiver 235 volt unregulated supply in lieu of the normal 150 volt regulated oscillator source.

Various values of damping resistance were also placed across the oscillator tuned circuit and further characteristics of oscillator frequency versus control voltage were taken. Figure 5 indicated a possible increase in frequency range with a two megohm damping resistance without too great a loss of linearity. However, the gain was considered marginal and the circuit was retained without the damper.

3.2 Reference Oscillator

Every attempt was made in the initial stages of the investigation to use the basic BFO of the receiver as the reference oscillator. However, difficulties encountered in extracting a stable, balanced output of sufficient amplitude and frequency range, indicated that a complete reference oscillator re-design would have to be undertaken to carry out the modification. Figure 6 shows the inadequate fre-

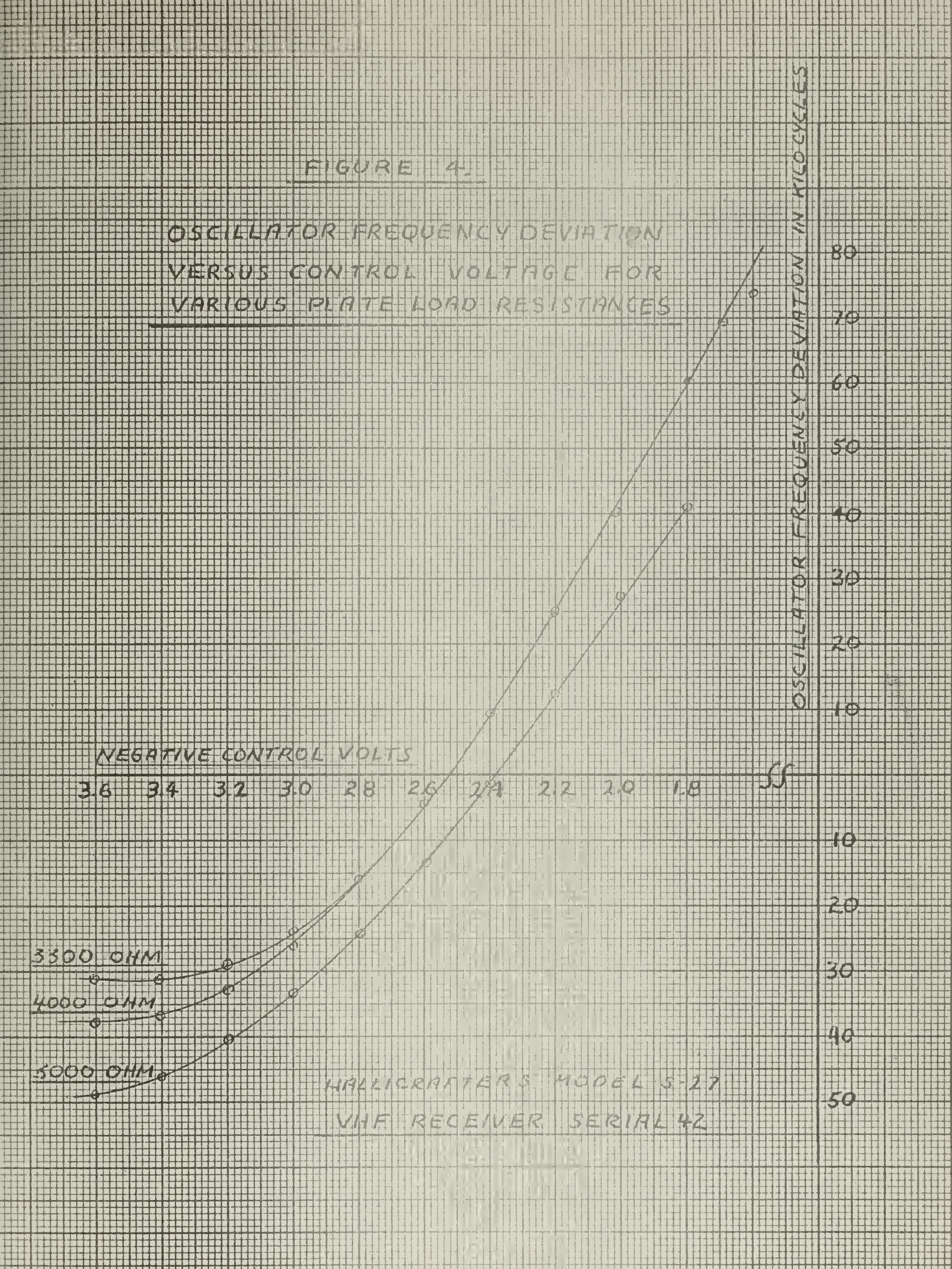


FIGURE 4.
OSCILLATOR FREQUENCY DEVIATION VERSUS CONTROL VOLTAGE FOR VARIOUS PLATE LOAD RESISTANCES
OSCILLATOR FREQUENCY DEVIATION IN KILOCYCLES
80
70
60
50
40
30
20
10
10
20
30
40
50
NEGATIVE CONTROL VOLTS
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
3300 OHM
4000 OHM
5000 OHM
HALLICRAFTERS MODEL S-27
VHF RECEIVER SERIAL 42

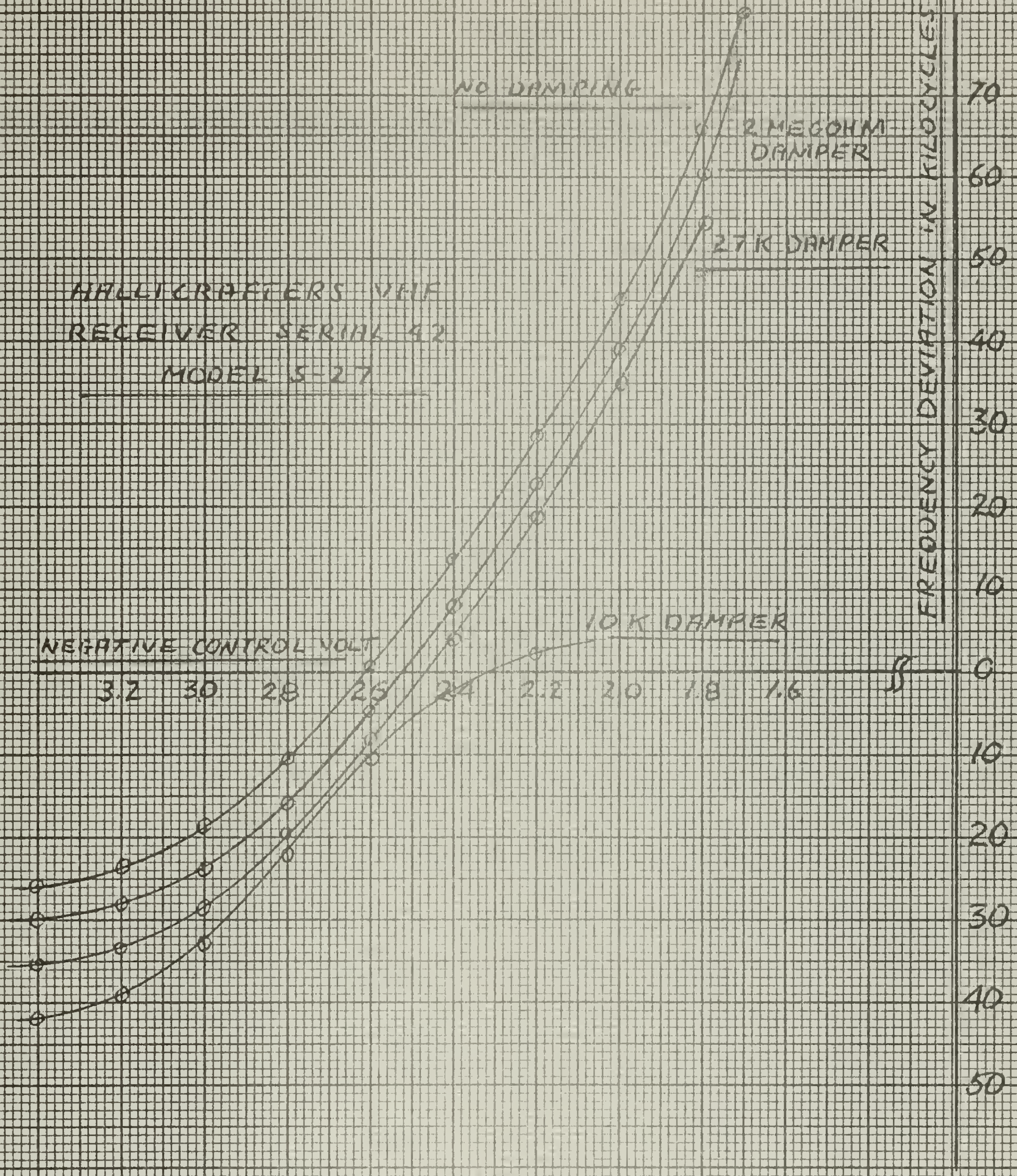
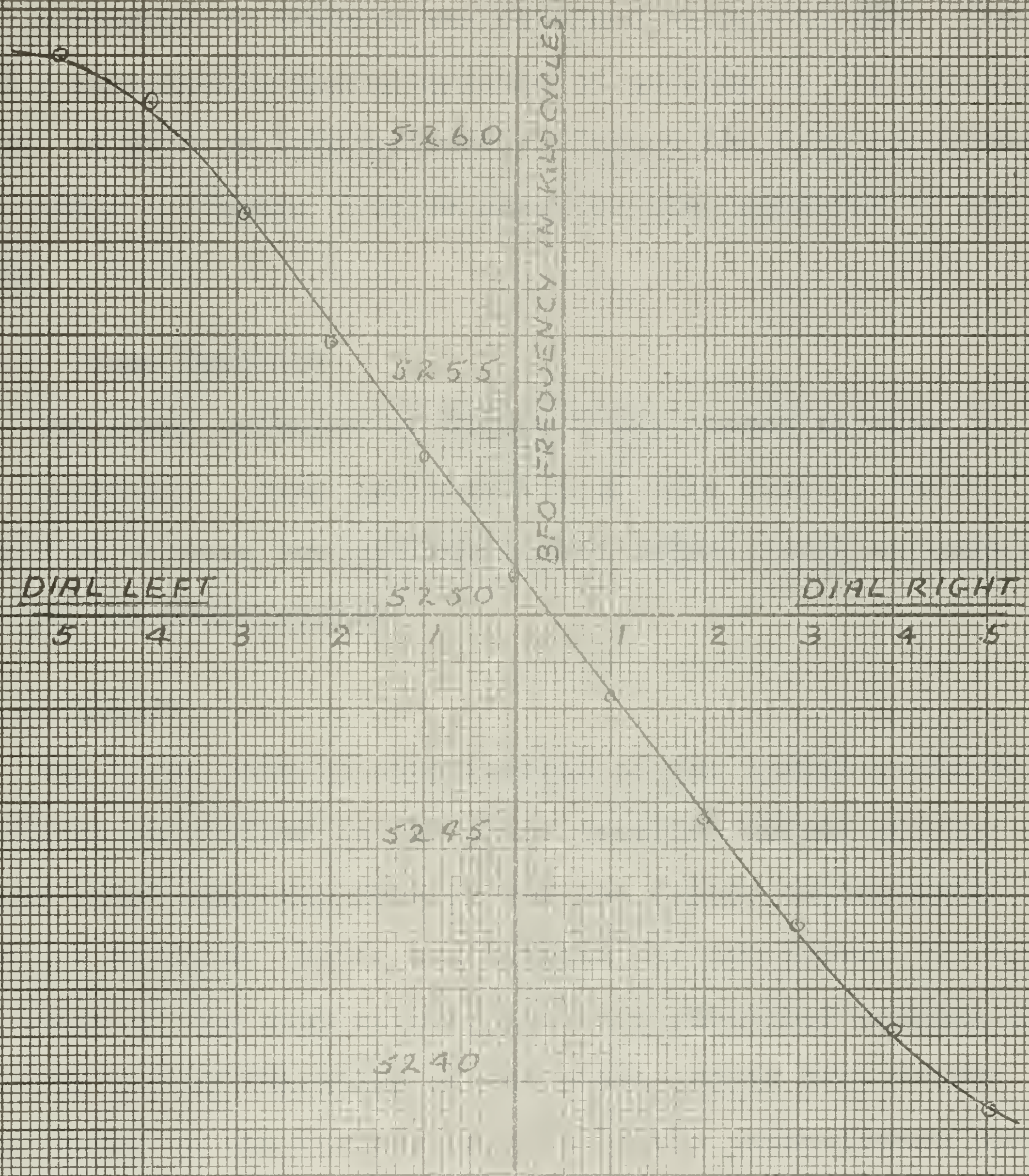


FIGURE 5.

OSCILLATOR FREQUENCY DEVIATION VERSUS CONTROL VOLTAGE FOR VARIOUS OSCILLATOR TANK DAMPING RESISTANCES

FIGURE 6.

BFO FREQUENCY VERSUS BFO DIAL CALIBRATION



HALLICRAFTERS MODEL S-27
VHF RECEIVER SERIAL 42

quency variation of the existing BFO versus BFO dial calibration.

A measure of success was obtained using the BFO. Its highly undesirable characteristic of pulling to the incoming signal as much as five kilocycles forced the test reference oscillator of Figure 7 to be used for the remainder of the study.

3.3 Phase Detector

The phase detector of Figure 6 was chosen because of its simplicity. Some optimization of this circuit was required to achieve the minimum locked-signal range necessary to test the modification.

3.4 Filter

The first step in optimization of the system would be to change the filter in the phase detector output so the signal power-spectral-density and the filter characteristics are matched. Jaffe and Rechtin /3/ and Weaver /6/ /7/ are three of the many authors who have published methods of analysis and optimization of the phase-locked loop filter. Other works on the various aspects of the phase-locked loop are listed in the bibliography.

The filter used in the phase detector output circuit was a simple RC low-pass configuration with a half-power frequency of 15 kilocycles. This half-power frequency was chosen because it is approximately equal to the half-power

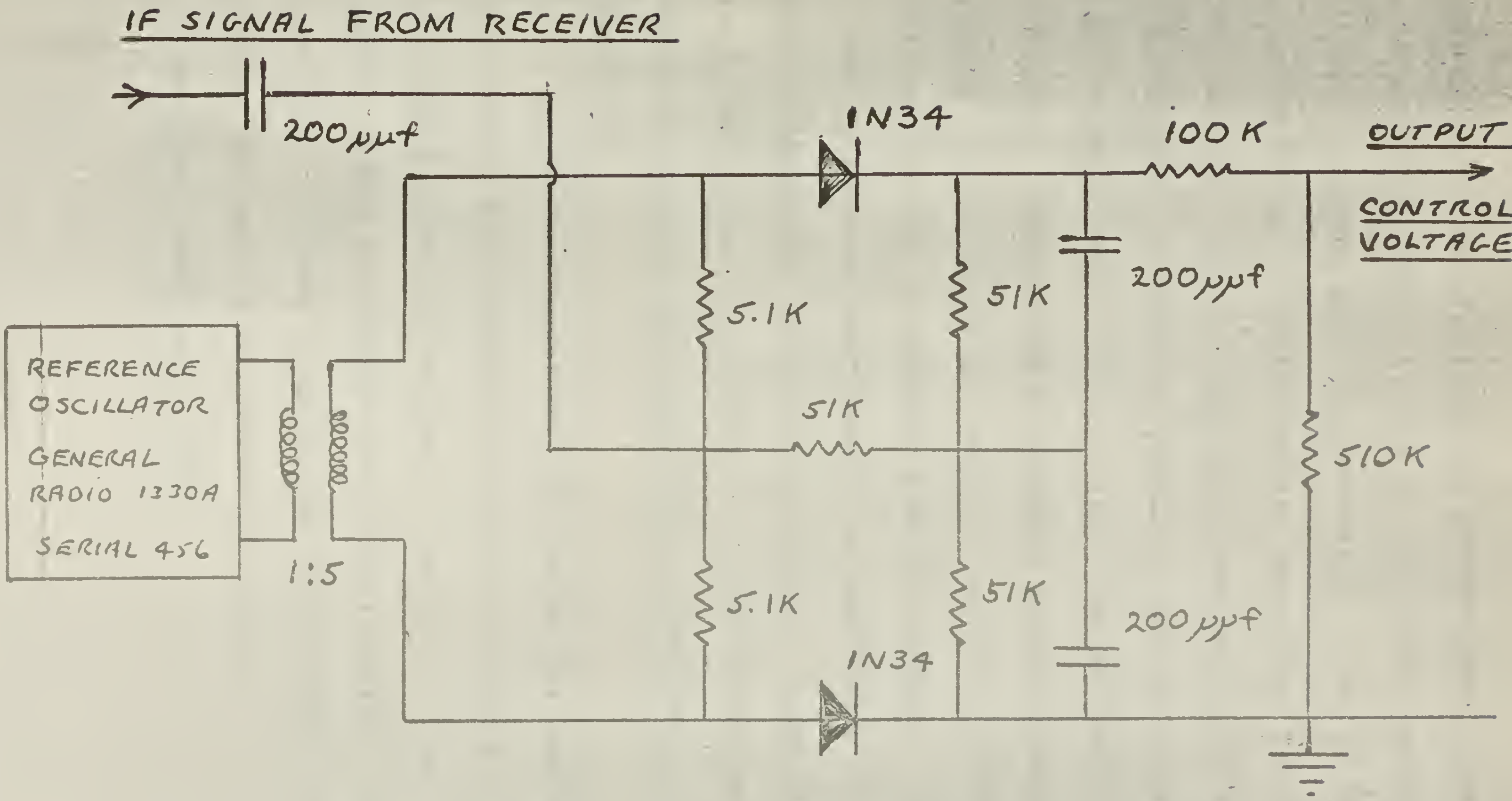


FIGURE 7. SCHEMATIC DIAGRAM OF PHASE DETECTOR AND REFERENCE OSCILLATOR

bandwidth of the receiver on narrow-band operation. In the experimental circuits, the 15 kilocycle bandwidth of the filter is comparable to operating in the HF band with a selectivity of 1.5 kilocycles, recalling the ten-to-one scaling factor. The 1.5 kilocycle bandwidth is considered representative of many HF receiver selectivities. Although the test results were taken at far from optimum conditions for the loop, the bandwidth normally called for, with signalling speeds of 286 words per minute, would be in the order of two kilocycles for the scaled down HF example. Hence, at least a thirty-percent improvement in bandwidth was realized without optimization of the loop filter. Signalling speeds up to 1,000 cycles per second or 2,860 words per minute, were examined without any noticeable deteriorization of signal waveform.

The keying speed of 100 cycles per second or 286 words per minute was chosen for the test results to provide data at keying speed in excess of the 60, 75, and 100 words per minute found in common use on many current radio-teletype circuits. Figure 8 shows the relationship between bauds, cycles per second and words per minute for the seven-unit teleprinter start-stop code.

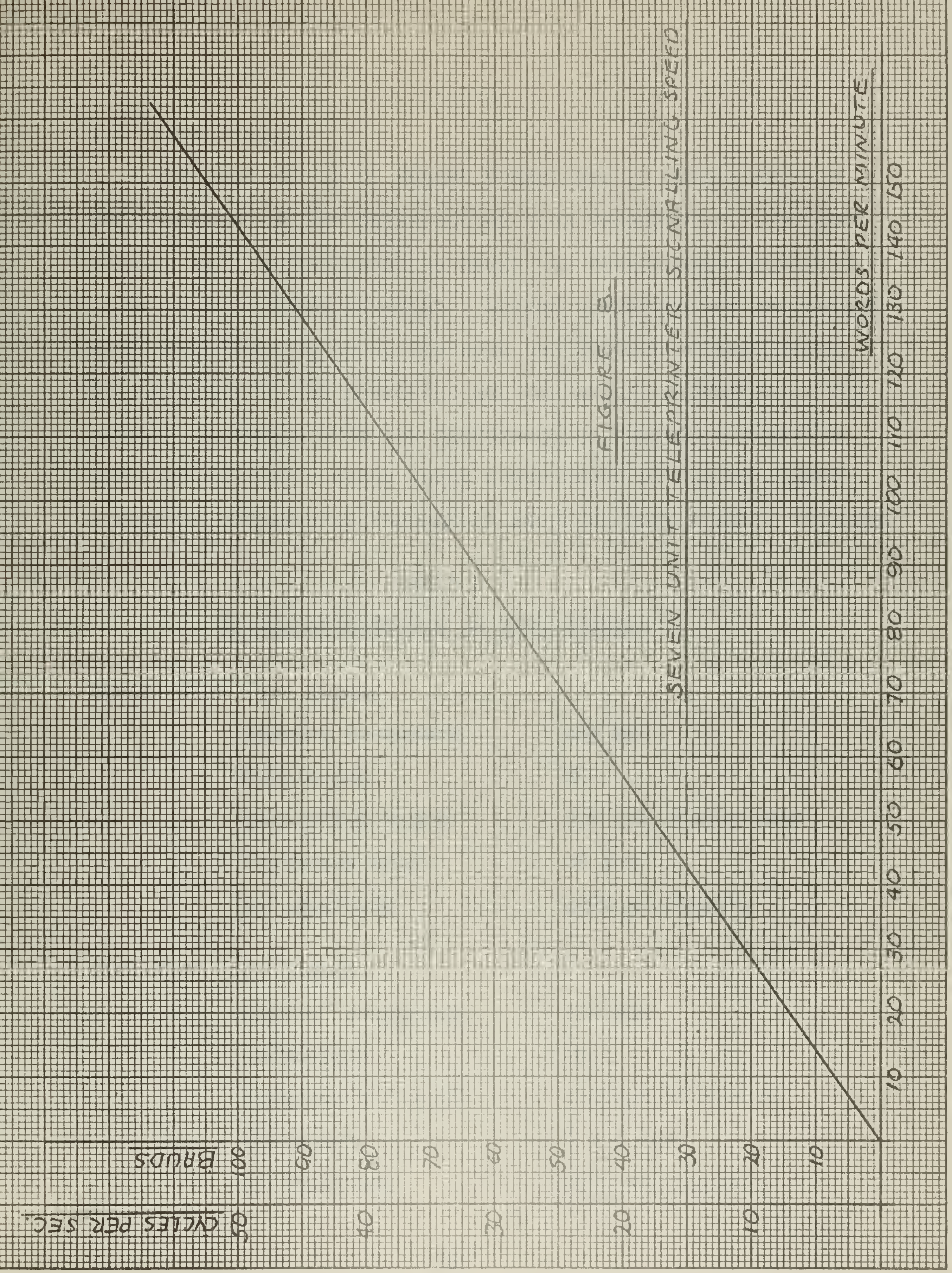


FIGURE 8
SEVEN UNIT TELEPRINTER SIGNALLING SPEED
WORDS PER MINUTE
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
BAUDS
10 20 30 40 50 60 70 80 90 100
CYCLES PER SEC.
10 20 30 40 50

4.0 Test Results

The test set-up of Figure 9 was used to obtain data on the operation of the phase-locked loop demodulator. Two test signals were investigated although the square-wave modulated signal was of prime interest. Locked operation was maintained with deviations up to 21 Kcs with the control voltage being proportional to the deviation and for signal strengths at the antenna terminals from 120 microvolts to 200,000 microvolts with the control voltage being independent of the RF signal strength. Figures 10 through 15 show the test results obtained.

TABLE 2

RF CHARACTERISTICS OF TEST SIGNALS

Square-Wave Test Signal	
Carrier Frequency	100 Mcs
Modulation	FM
Modulation Signal	100 cps square-wave
Frequency Shift	10 Kcs
RF Amplitude	4000 microvolts
Sine-Wave Test Signal	
Carrier Frequency	100 Mcs
Modulation	FM
Modulation Signal	100 cps sine-wave
Deviation	± 5.5 Kcs
RF Amplitude	4000 microvolts

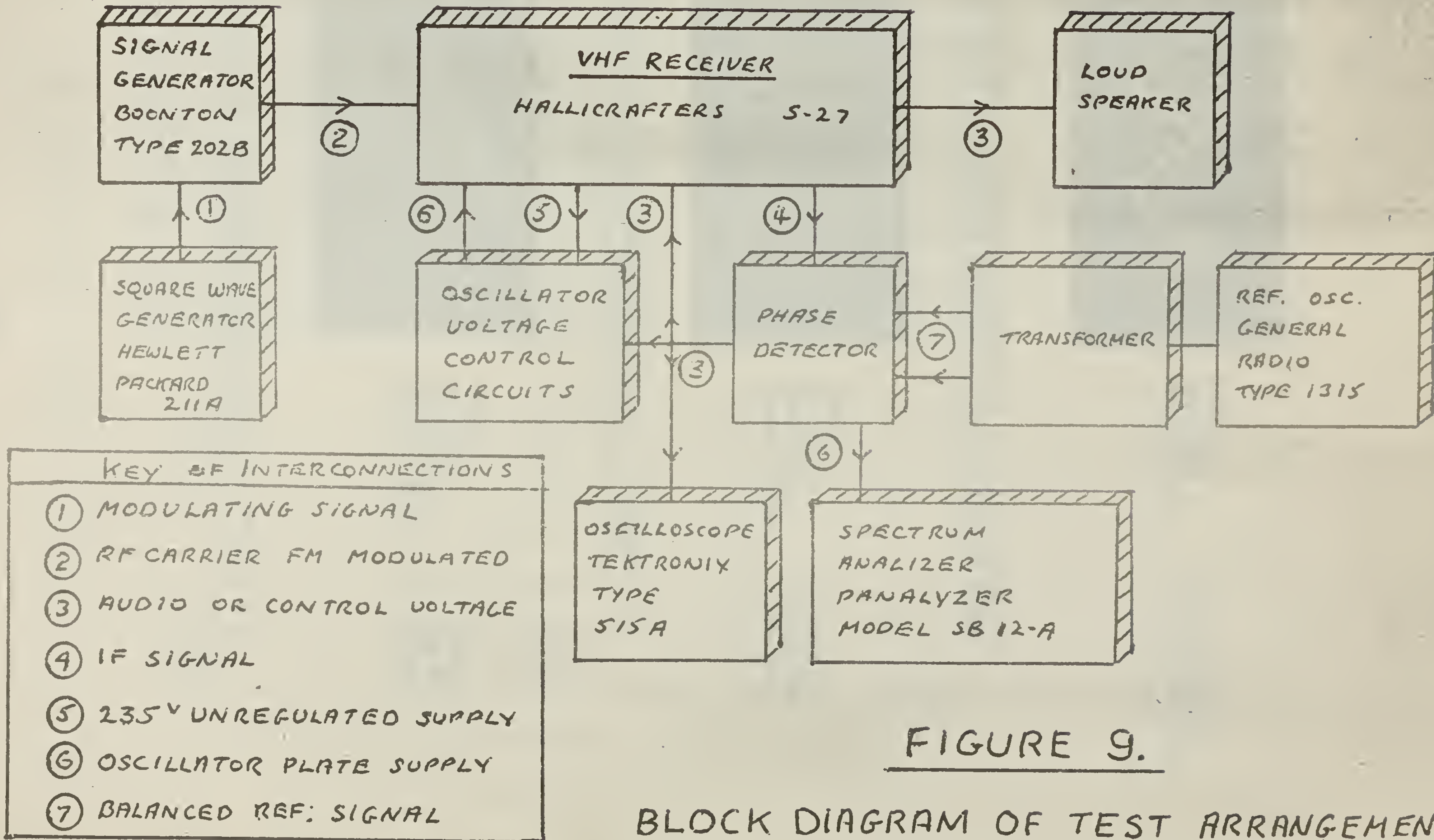
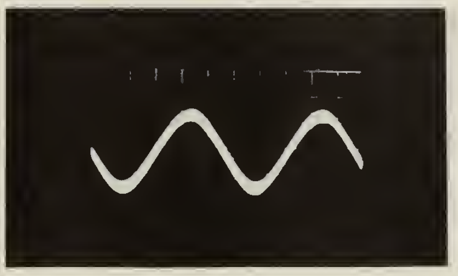


FIGURE 9.

BLOCK DIAGRAM OF TEST ARRANGEMENT



Scale
Vertical 0.2 volt/div.
Horizontal 1 millisec/div.

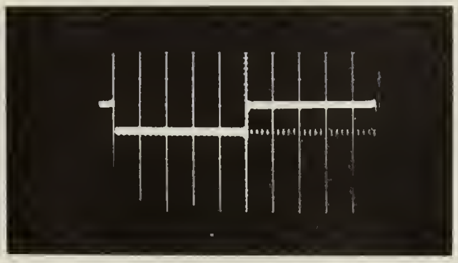
Figure 10. Sine-Wave Modulation — Audio Output or Control Voltage in Phase-Locked Mode

Scale
Vertical 5 db/div.
Horizontal 1 Kcs/div.
Center Freq. 5.25 Mcs

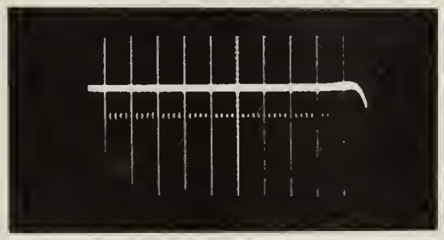
Figure 11. Sine-Wave Modulation — IF Output of Receiver in Phase-Locked Mode

Scale
Vertical 5 db/div.
Horizontal 3 Kcs/div.
Center Freq. 5.25 Mcs

Figure 12. Sine-Wave Modulation — IF Output of Receiver in Normal Mode

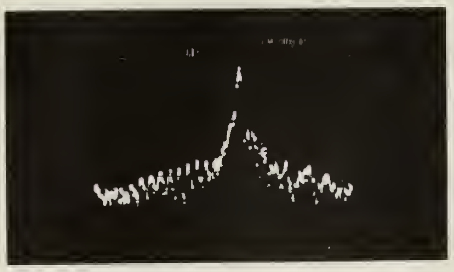


Scale	
Vertical	0.5 volt/div.
Horizontal	1 millisec/div.



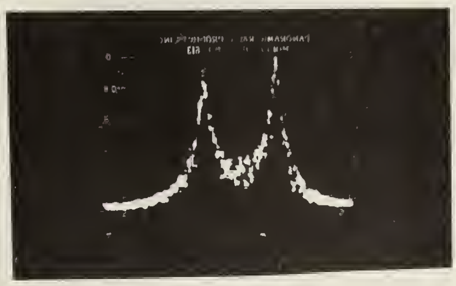
Scale	
Vertical	0.5 volt/div.
Horizontal	0.1 millisec/div.

Figure 13. Square-Wave Modulation - Audio Output or Control Voltage in Phase-Locked Mode



Scale	
Vertical	5 db/div.
Horizontal	1 Kcs/div.
Center Freq.	5.25 Mcs

Figure 14. Square-Wave Modulation - IF Output of Receiver in Phase-Locked Mode



Scale	
Vertical	5 db/div.
Horizontal	3 Kcs/div.
Center Freq.	5.25 Mcs

Figure 15. Square-Wave Modulation - IF Output of Receiver in Normal Mode

5.0 Analysis of the Phase-Locked Loop

The design and optimization of the phase-locked loop demodulator is aided considerably by the mathematical model of Figure 16. This model shows the loop to be nothing more than a simple second-order control system with the following design variables:

a) Filter transfer function, H (s)

b) Phase-detector transfer function, Kp

c) Voltage-controlled oscillator transfer function, Kvco

The driving function investigated, both analytically and experimentally, was the step-frequency or ramp-phase input which is the most applicable to the frequency-shift radioteletype problem.

The following basic assumptions were made in construction of the mathematical model:

a) The system was approximated as linear. For example, the phase detector transfer function, Kp, is assumed directly proportional to the difference of signal and reference phase rather than to the sine of the difference.

b) The receiver mixer and amplifiers do not affect loop phase.

Generally no attempt was made in this investigation to optimize the system experimentally and only those changes that were necessary to show the demodulator would indeed function were made to the original circuits. When phase-

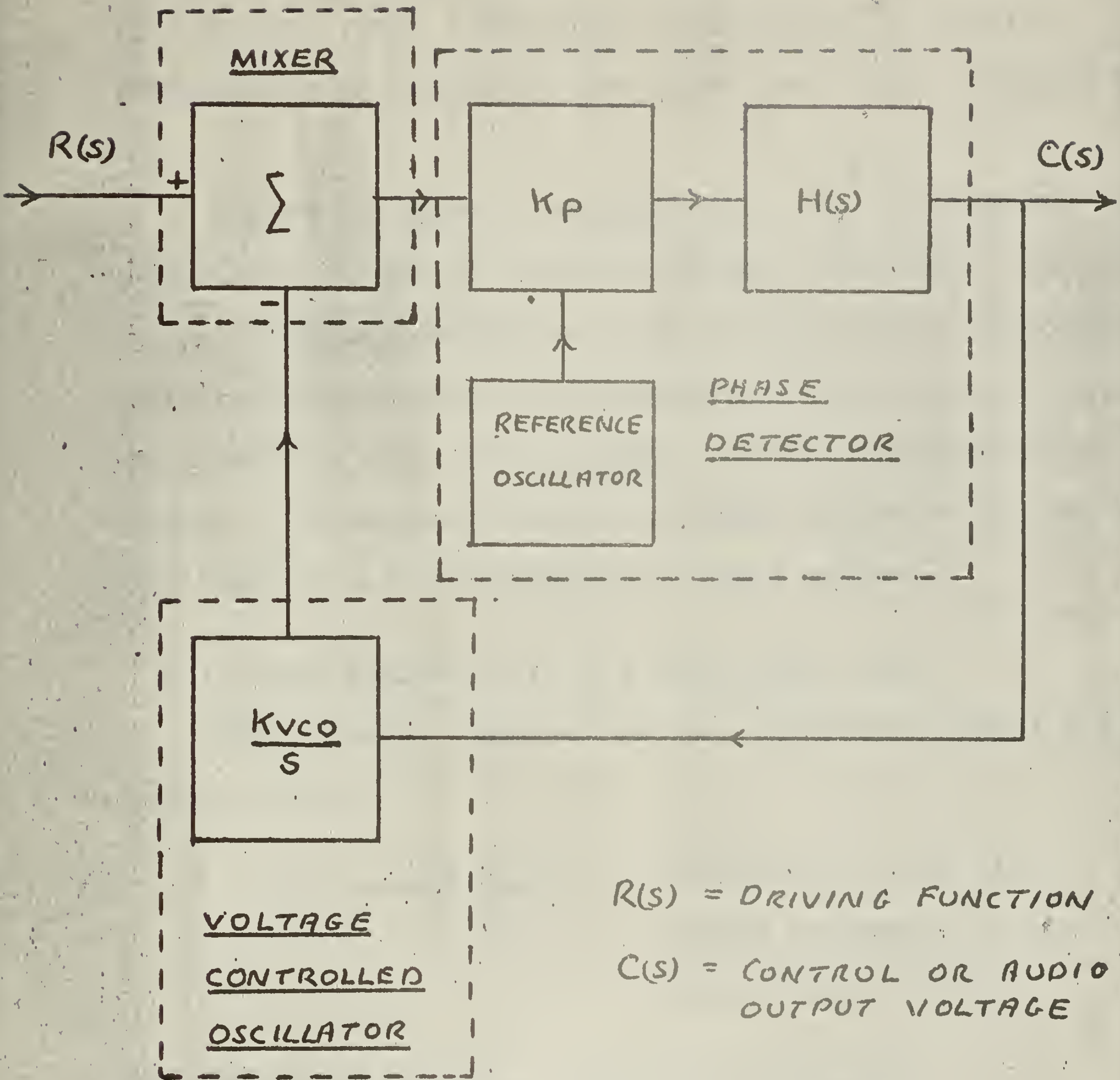


FIGURE 10.

BLOCK DIAGRAM OF PHASE-LOCKED LOOP DEMODULATOR

locked loop operation was obtained, the two transfer functions, Kp and Kvco, were determined experimentally using the test arrangement of Figure 17 and data from Figure 18 and Figure 19.

Figure 20 shows a comparison of the experimental and analytical output or control-voltage waveforms. The results of this comparison indicate the linearization assumptions made in constructing the mathematical model were reasonable and that the model would indeed aid in optimization of the system. The analog computer is most suitable for the investigation and optimization of such systems.

5.1 Loop Analysis for the Phase-Ramp Input

The transfer function of the low-pass filter, H (s), has the form:

$$H(s) = \frac{1}{S + W_1}$$

where W_1 is the half-power frequency of the RC low-pass filter

The open-loop transfer function is given by:

$$\frac{C(s)}{R(s)} = Kp\, H(s)$$

where Kp is the phase-detector transfer function

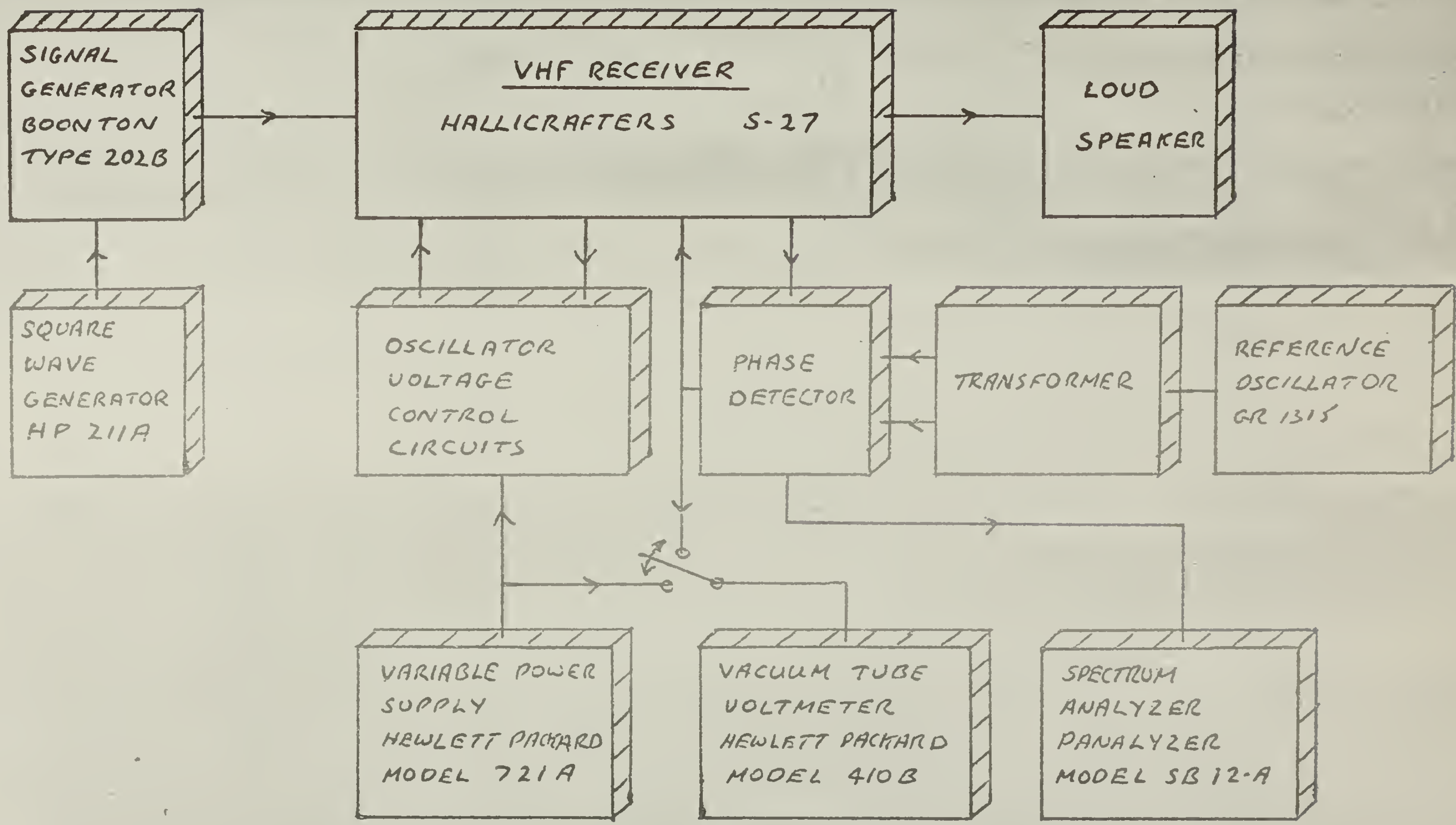


FIGURE 17.

BLOCK DIAGRAM FOR EXPERIMENTAL DETERMINATION OF K_p & K_{vco}

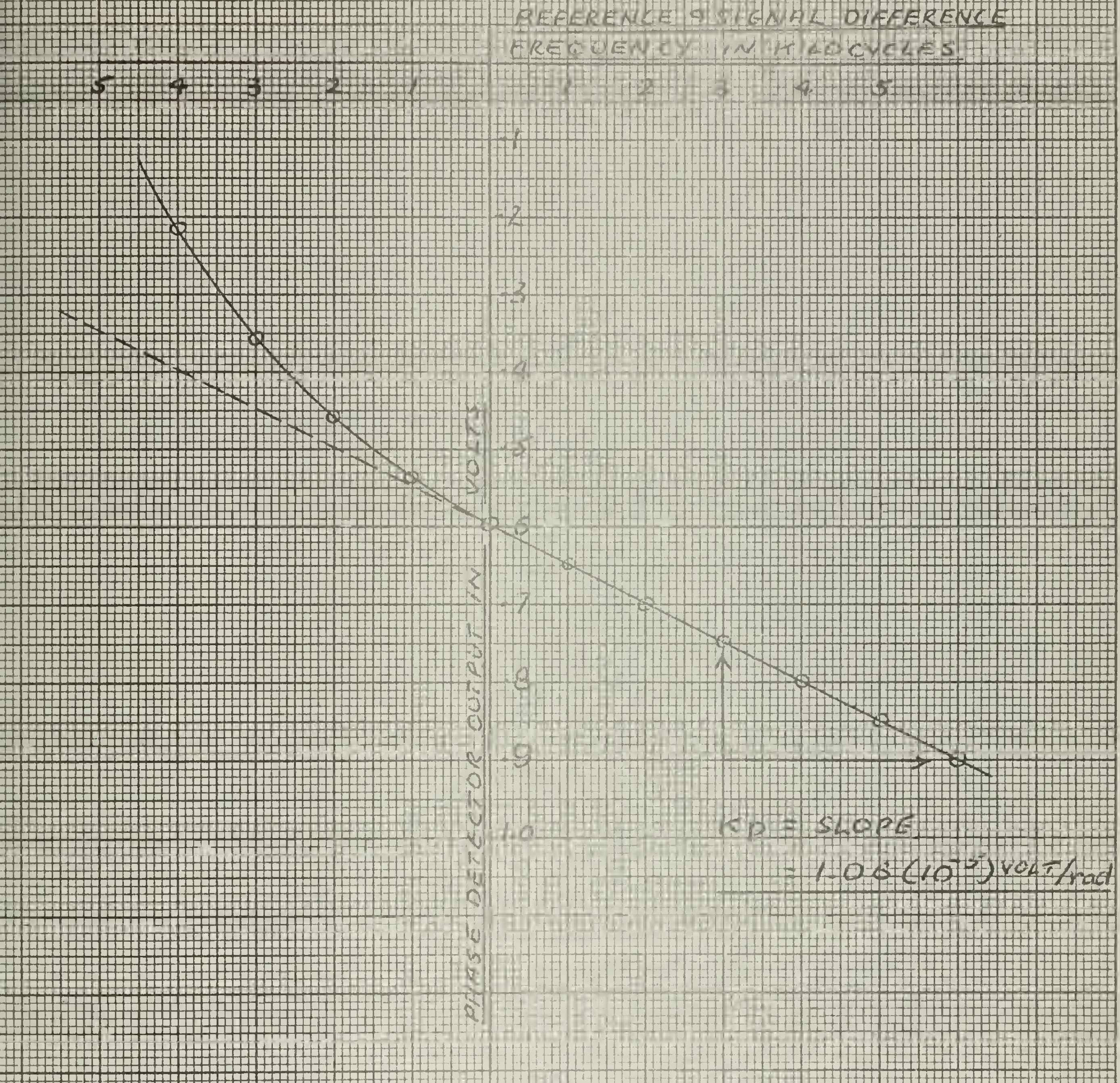


FIGURE 18

EXPERIMENTAL DETERMINATION
PHASE DETECTOR TRANSFER
FUNCTION - Kp

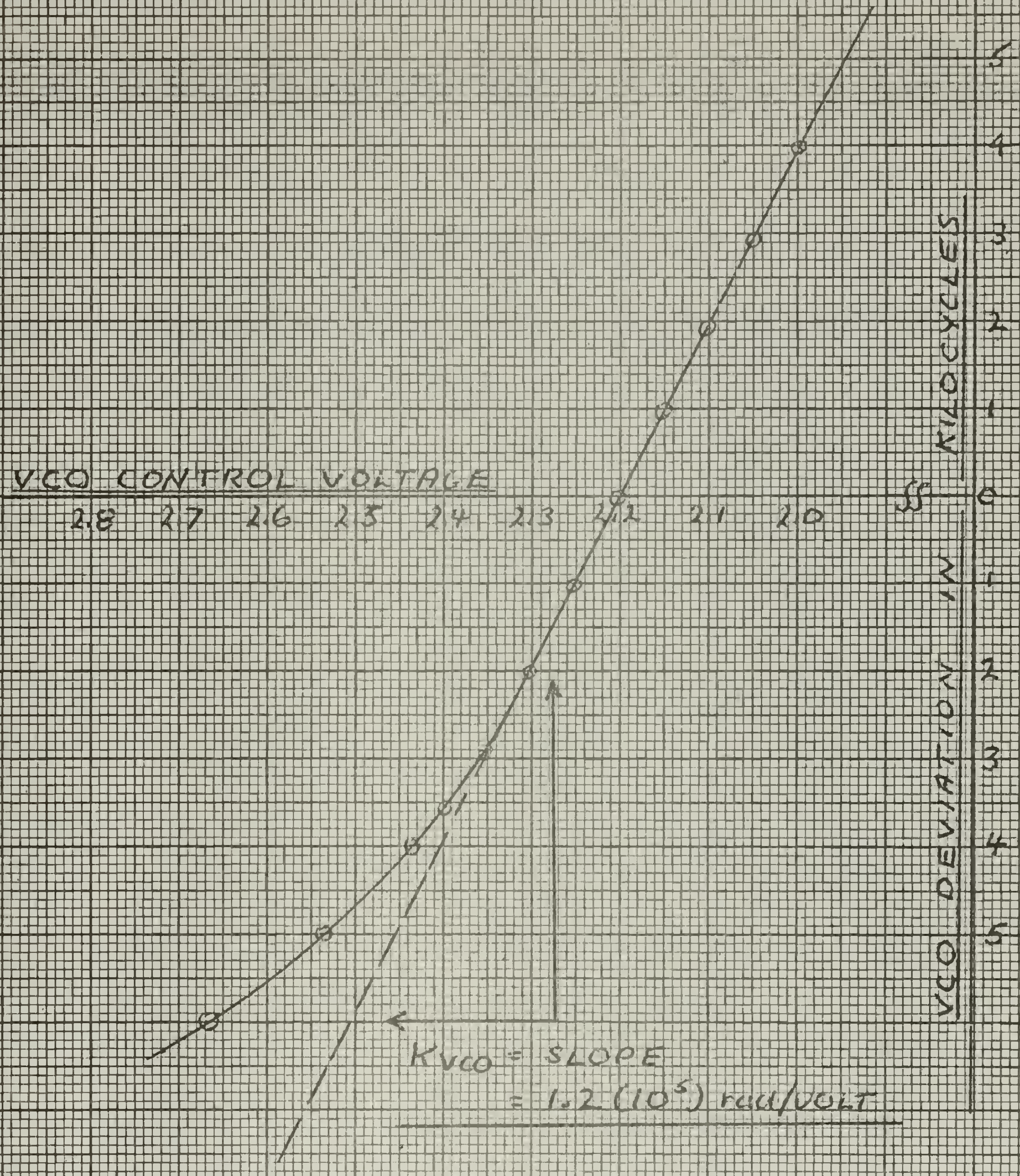


FIGURE 19.

EXPERIMENTAL DETERMINATION OF VOLTAGE CONTROLLED OSCILLATOR TRANSFER FUNCTION - KVCO

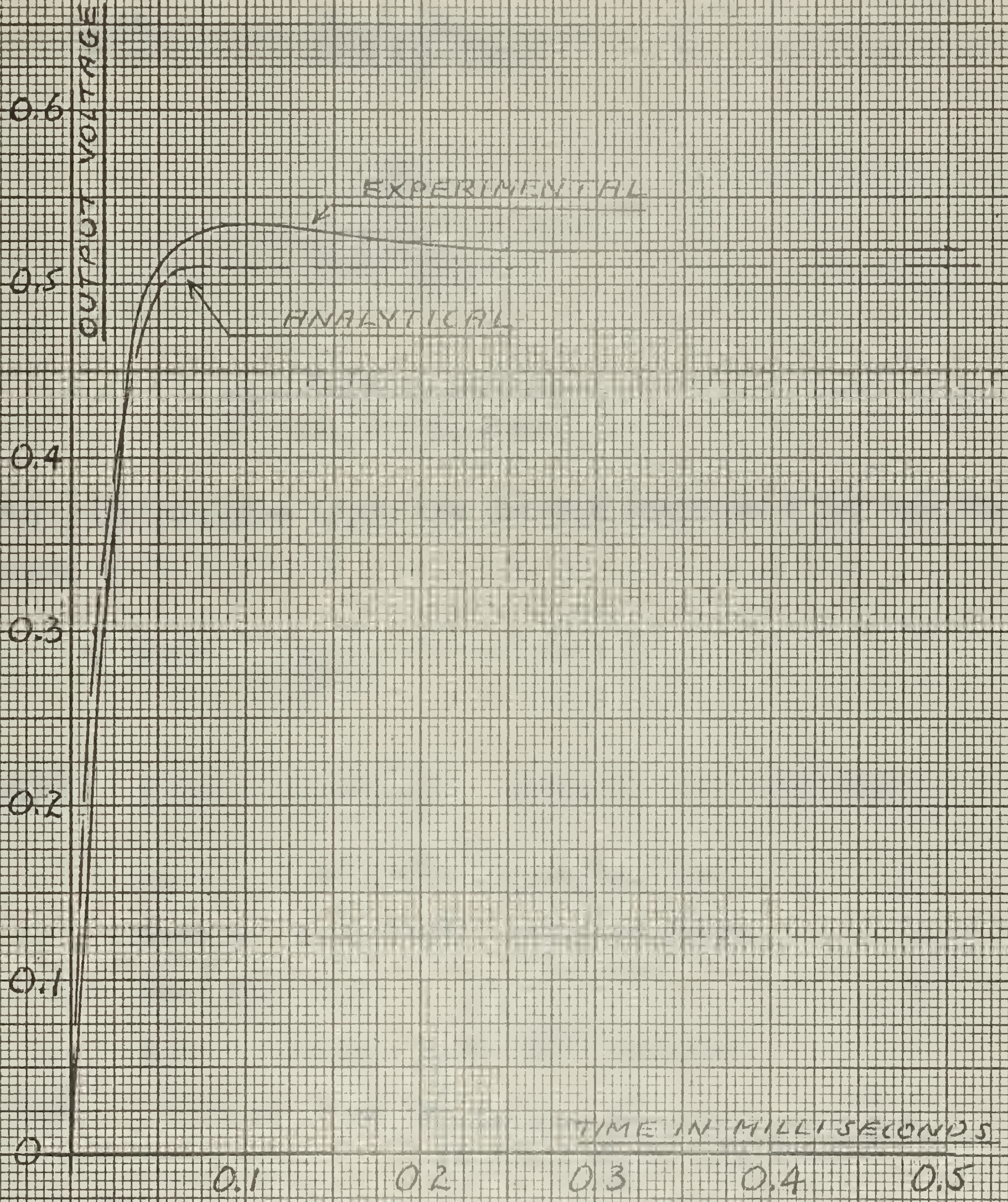


FIGURE 20.
ANALYTICAL AND EXPERIMENTAL
COMPARISON OF OUTPUT WAVEFORM

The closed-loop transfer function has the form:

$$\frac{C\ (s)}{R\ (s)} = \frac{Kp\ H\ (s)}{1 + \frac{Kp\ H\ (s)\ Kvco}{s}}$$

$$= \frac{\frac{Kp}{S + W_1}}{1 + \frac{Kp\ Kvco}{S(S + W_1)}}$$

$$= \frac{S\ Kp}{S^2 + W_1\ S + Kp\ Kvco}$$

For ramp-in-phase input the driving function R (s) has the form:

$$R\ (s) = \frac{Ro}{S^2}$$

With $H\ (s) = \frac{1}{(S + 10^5)}$ where $W_1 = 10^5$ rad./sec.

$Kp = 1.06\ (10^{-5})$ volt/rad./sec.

$Kvco = 1.24\ (10^5)$ rad./sec./volt

$Kvco\ Kp = 1.3$

$Ro = 10$ Kcs $= 6.28\ (10^4)$ rad./sec.

Then $$C\ (s) = Ro\ Kp \left[\frac{1}{S\ (S^2 + W_1\ S + Kp\ Kvco)} \right]$$

$$= Ro\ Kp \left[\frac{1}{S\ (S + a)\ (S + b)} \right]$$

The inverse transform of

$$\frac{1}{S\ (S + a)\ (S + b)} = \frac{1}{a\ b} + \frac{b\ e^{-at} - a\ e^{-bt}}{ab\ (a - b)}$$

Then $$C\ (s) = 6.28\ (10^{4})\ 1.06\ (10^{-5}) \left[\frac{1}{S\ (S^{2} + 10^{5} S + 1.3)} \right]$$

let $S^{2} + W_{1} S + Kp\ Kvco = 0$

$$S^{2} + 10^{5} S + 1.3 = 0$$

$$(S + 10^{5})\ (S + 1.3(10^{-5})) = 0$$

hence $a = 10^{5}$

$b = 1.3\ (10^{-5})$

$ab = 1.3$

$ab(a-b) = 1.3\ (10^{5})$

$$C\ (t) = Kp\ Ro \left[\frac{1}{ab} + \frac{b\ e^{-at}}{ab(a-b)} - \frac{a\ e^{-bt}}{ab\ (a-b)} \right]$$

$$= 0.66 \left[\frac{1}{1.3} + \underbrace{\frac{1.3\ (10^{-5})e^{-10^{5}t}}{1.3\ (10^{5})}}_{\to 0} - \frac{10^{5}\ e^{-1.3(10^{-5})t}}{1.3\ (10^{5})} \right]$$

<u>$C\ (t) = 0.51 \left[1 - e^{-1.3\ (10^{-5})t} \right]$ volts</u>

Where C(t) is the mathematical expression for the output or control voltage.

6.0 Conclusions

Although the modified receiver was not used on an actual radio-teletype circuit, the test results obtained show definite advantages for the phase-locked loop demodulator. The test results, scaled down from VHF to HF, are summarized in Table 3 and include references to the improvements in selectivity and stability obtained over the original receiver.

TABLE 3

SUMMARY OF TEST RESULTS

Maximum Shift	2 Kcs
Minimum Shift	Effectively zero
IF Selectivity	Signal normally requiring 2 Kcs bandwidth passed through 1.5 Kcs amplifier without phase-locked loop optimization
Stability	Stability of receiver equals stability of reference oscillator, a required addition to circuitry
RF Signal Strength	Control voltage, signal output, was independent of RF signal strength over range of 66 db using a limiter output from the receiver
Keying Speed	Although tests and analysis were carried out at 100/cps (286 wpm) the control voltage remained essentially 'square' for keying speeds ranging from zero to greater than 1000 cps or 2860 wpm

The difficulties encountered in endeavoring to use the

existing receiver BFO as a reference oscillator indicates that the entire BFO circuitry of the receiver should be replaced with a highly stable fixed-frequency oscillator with switched frequency adjustment for the various modes of operation such as CW, A1, or phase-locked loop for the teletype, F1, and facsimile, F4, modes.

The existing limiter in the S-27 receiver was used during the tests. It is considered that the final IF amplifier of any receiver being modified for phase-locked loop operation should be altered to provide limiting action and that such action should be controlled by the phase-locked loop mode of operation switch.

If a larger range of operation in the phase-locked loop mode is required, for example, reception of entertainment FM broadcasts, then the non-linearities in the voltage-control circuits of the local oscillator will require further investigation and improvement. It is these non-linearities that were doubtlessly responsible for limiting the locked-signal range of the test equipment.

It is considered that further investigation is required of the signal processing and the circuit modifications needed to the frequency-shift convertors such as the AN/URA 8 and AN/URA 17 to permit these units to operate the terminal equipment from the receiver output. Cursory examination of the circuits in the convertors indicate only minor changes, that is, switching of inputs and possibly the addition of a

limiting amplifier, would be required if the receiver output were injected into the convertor immediately after the audio discriminator.

Among the typical communications receivers considered suitable for this modification are the RB Series manufactured by Federal and Radio Corporation of America, the CSR5 Series manufactured by Canadian Marconi Company, and the B28 and subsequent models manufactured by Marconi's Wireless Telegraph Company. Figure 21 shows the block diagram of the Hallicrafters S-27 Receiver with the schematic of the complete phase-locked loop modification added.

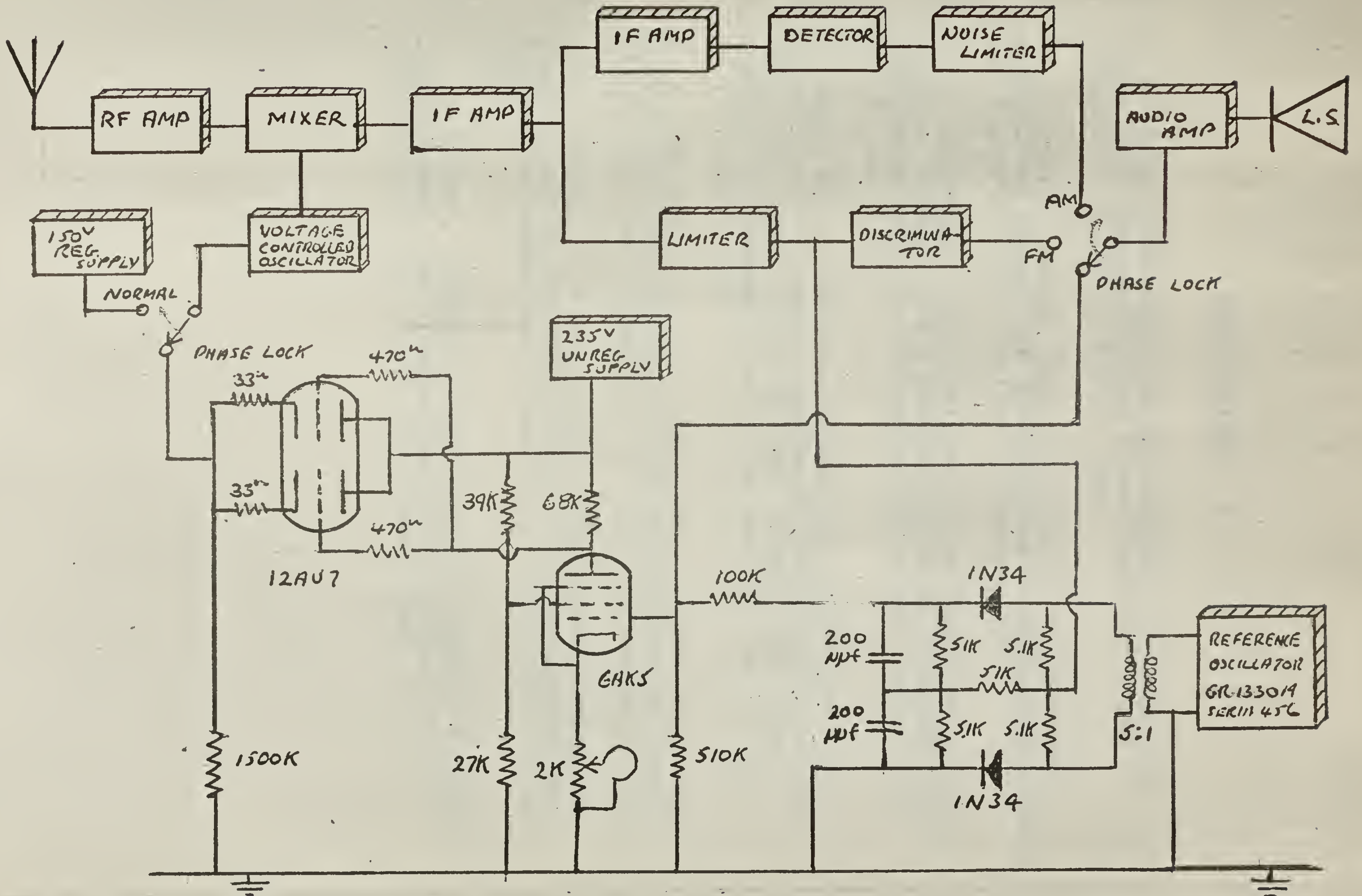


FIGURE 21. SCHEMATIC DIAGRAM OF PHASE-LOCKED LOOP MODIFICATION

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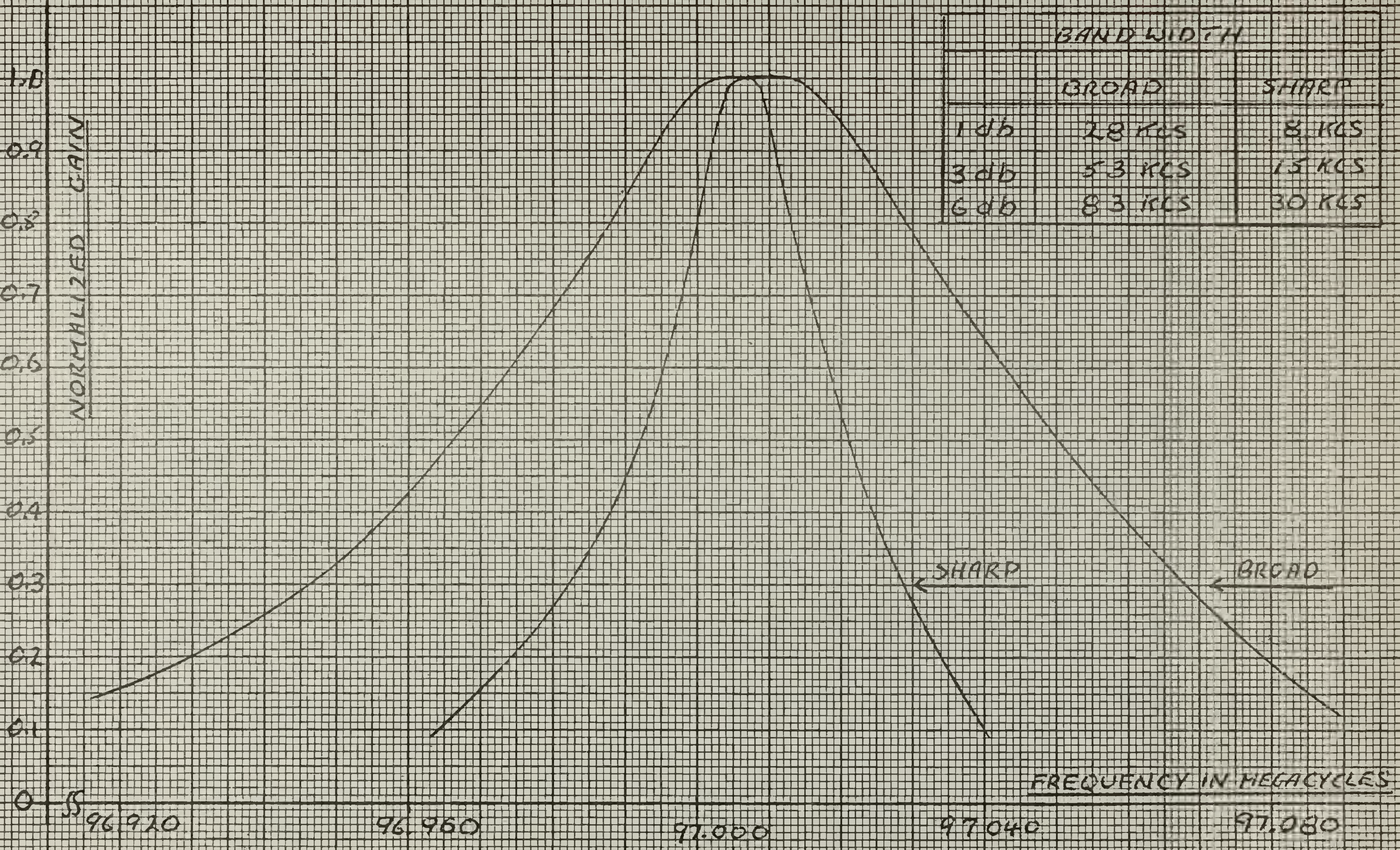
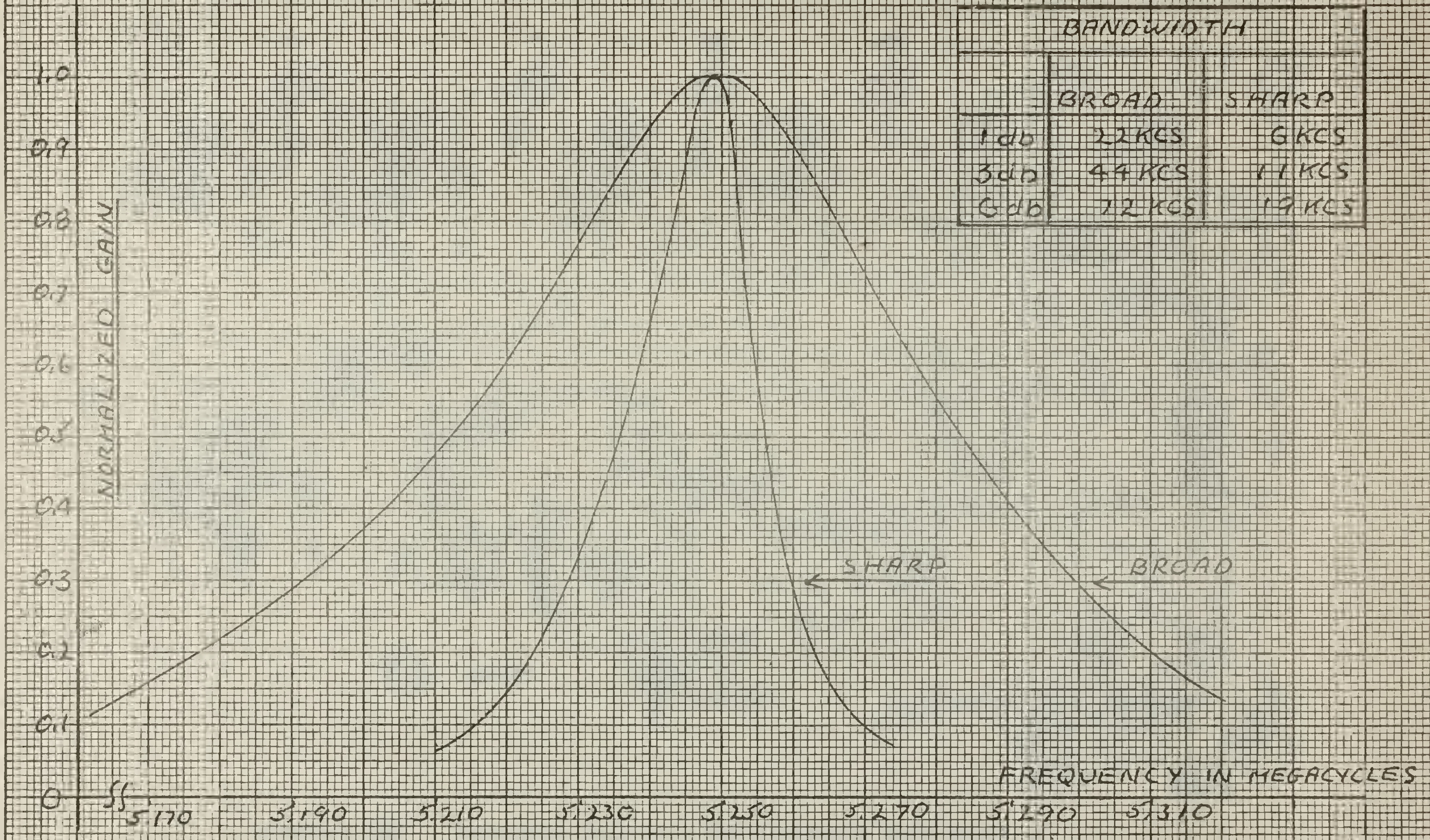
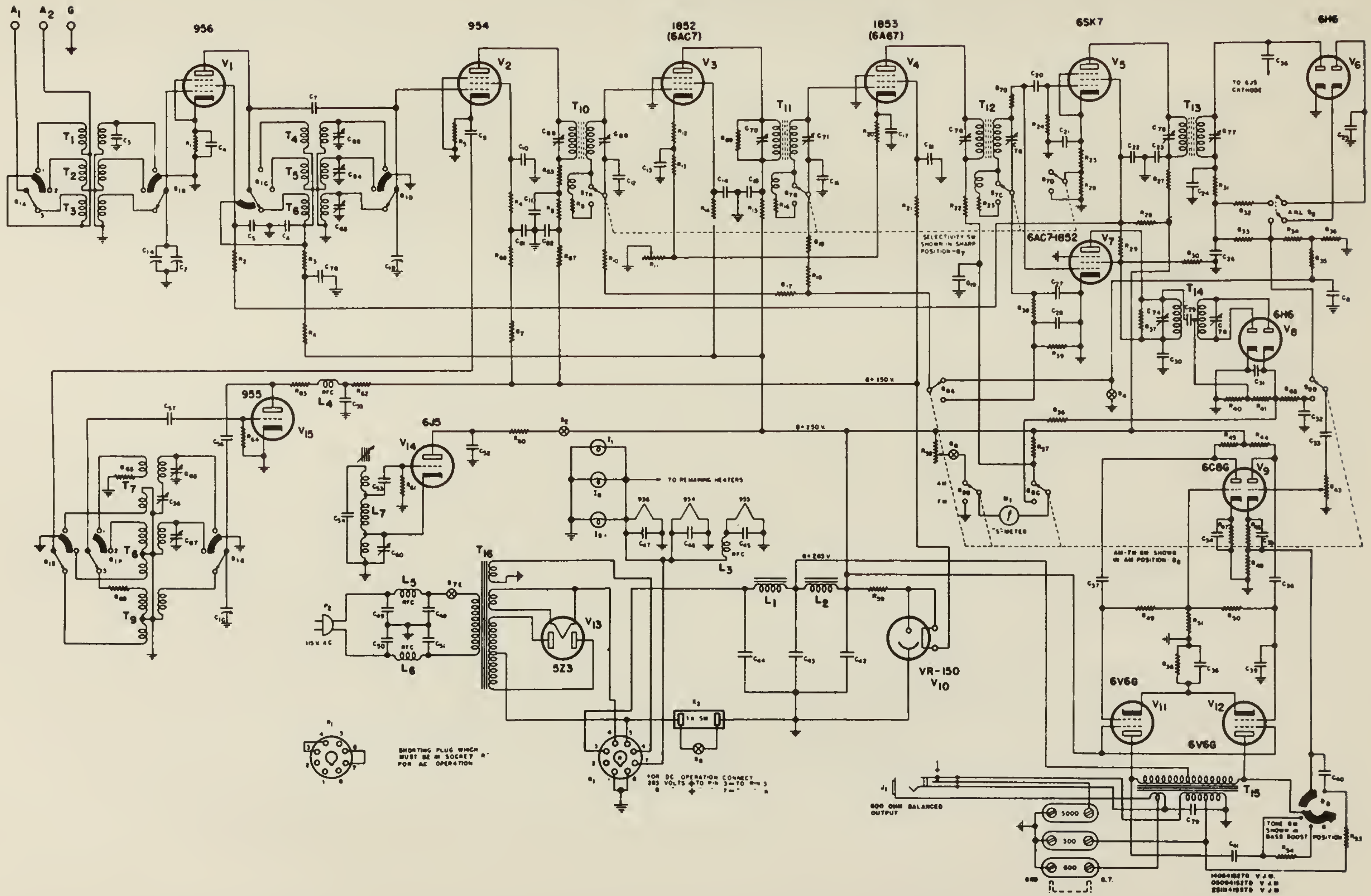


APPENDIX I OVERALL SELECTIVITY CURVES - HALLICRAFTERS
S-27 VHF RECEIVER SERIAL 42 6 NOV. 1962



BANDWIDTH		
	BROAD	SHARP
1 db	22 KCS	6 KCS
3 db	44 KCS	11 KCS
6 db	72 KCS	19 KCS

APPENDIX II IF SELECTIVITY CURVES - HALLICRAFTERS S-27 VHF RECEIVER SERIAL 42 6 NOV. 1962



APPENDIX III   Schematic Diagram - Hallicrafters S-27 Receiver